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The Use of Models in Science and Science Teaching

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The word 'model' is used in many different ways in everyday life. Thus 'a model' is a person of striking appearance, while a 'model home' is represented as an ideal to be sought after, and a 'model car' is a toy given to children. Equally varied are the meanings in academic life. This paper discusses the types and uses of models found in science and science teaching. It explores the contention that the misuse of models in science teaching can lead to misunderstandings by students of both models and their embodied concepts. Such misunderstandings are particularly important at the school/higher education interface as they can contribute to later academic failure (Gilbert 1977).

What kinds of academic model are there?

Black (1962) classifies models into five types: scale (elsewhere called iconic); analogue; mathematical; theoretical; archetypal.

Scale models are 'likenesses of material objects, systems or processes, whether real or imaginary, that preserve relative proportions'. Examples are: dams (used in civil engineering), parts of anatomy (used in medicine), Solvay towers (used in chemical engineering). The following generalizations can be made about them:

(1) They are usually constructed for a specific purpose or purposes. As such they have faithful representations of those aspects of the original which are thought to be relevant to the intended use.
(2) As a consequence of these assumptions, every scale model has associated with it, 'conventions of interpretation' relating the model to the original. The usual practice is to have an invariance of linear proportionality, but only a partial identity of other properties, with the original. Thus a model aeroplane may have the same shape as the original but be incapable of flight because the wing area/weight ratio is not maintained in the model.
(3) These 'conventions of interpretation' must be fully spelt out and any inferences drawn from a model carefully validated on the original.

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In this paper this class of models will be assumed to include diagrammatic representations of scale models and this broader group of models will be termed 'iconic'.

Analogue models represent 'some material object, system, or process designed to produce as faithfully as possible in some new medium the structure or web of relationships in the original'. Furthermore, an adequate analogue model 'will manifest a point-by-point correspondence between the relations it embodies and those embodied in the original: every incidence of a relation in the original must be echoed by a corresponding incidence of a correlated relation in the analogue model'. Thus the analogue model 'shares with the original not a set of features or an identical proportionality of magnitudes but, more abstractly, the same structure or pattern of relationships' (Black 1962). Examples include: ball-and-stick structure of crystals (used in chemistry), cybernetic representations of organ function (used in biology).

Hesse (1966) divides any analogy up into three parts: the positive analogy (those properties of the model which are wanted to describe the explicandum, i.e. the thing or situation to be described); the negative analogy (those parts of the model which are definitely not transferable to the explicandum); and the neutral analogy (those parts of the model which are not yet known to be positive or negative, and which allow predictions to be made).

In designing a model, emphasis is usually placed on the 'positive analogy', although much insight can be gained from a study of the negative analogy, i.e. where the model breaks down. Gee (1978) has spelt out the positive analogy of the hydrodynamical model used by Maxwell for electrostatic phenomena associated with Faraday's lines of force. This is given below:

Electrostatic phenomenon:	*Hydrodynamical analogue:*
Incorporeal fluid ether.	'Infinite' sea.
Positive charge.	Source.
Negative charge.	Sink.
Line of force.	Tube of flow.
Field strength.	Direction and speed of flow.
Electrical potential difference.	Difference in fluid pressure.
Surface charge density.	Rate of flow per unit area.
Dielectric medium.	Fluid with viscous drag.

An analogue model is seen to be the sum of a series of properties corresponding to those of the original (or explicandum), i.e.:

Explicandum	*Model*
Property_1	Property_a
Property_2	Property_b

and the conditions for a 'positive analogy' are as follows:

(1) The horizontal relations between properties of the explicandum and model, for example between Property_1 and Property_a can be

described in terms of degree of similarity. Thus 'field strength' and 'direction and speed of flow' are perceived to have a strong relationship, i.e. to be readily perceived and having a good explanatory function, whilst 'surface charge density' and 'rate of flow per unit area' are weakly related, i.e. the relationship is more difficult to envisage and serves a less precise purpose.

(2) The relationship between properties of the model, for example between 'source' and 'sink', are strongly related, as are those of the explicandum, for example between 'positive charge' and 'negative charge'.

(3) All the main perceived characteristics of the explicandum can be identified as being accounted for in the 'positive analogy' or, at least, as not forming part of the 'negative analogy'.

A *mathematical model* is one 'that can be summarized in, or represented by, a mathematical equation' (Davies 1978). Mathematical models are seen as having the following characteristics:

(*a*) The original phenomenon is thought of as 'projected' upon a collection of sets and functions, such that each symbol corresponds to a definite concept in the original.

(*b*) The model, being simpler and more abstract than the original, must be accompanied by a catalogue of conditions imposed on its use.

Such models are much prized, for the simplifications that they introduce, coupled to the relative ease by which they can be manipulated, enable complex phenomena to be rapidly and comprehensively explored.

Theoretical models involve the production of some concretized representation of the phenomenon, which can be applied to the study of the phenomenon without making theoretical assumptions about it. One approach to such models relates them to the phenomenon in an 'as if it were' manner, i.e. an argument by analogy such as 'a magnetic field acts as if it consisted of lines of force joining north and south poles'. The second approach involves an 'as it is' view, i.e. an identification like a metaphor such as 'a magnetic field consists of lines of force which join north and south poles'. The first, and more detached, approach makes explanations difficult. The second does permit explanations but can lead to self-delusion when the myth is confounded with reality. The model need not be actually constructed, and can merely be a way of discussing the phenomenon, but here the realization of constraints which would be felt in such an attempt are not felt, and the boundaries of the model not fully explored.

Theoretical models tend to be communicated as verbal or diagrammatic models. Although sometimes perceived as being 'pictures' of the phenomenon, the real attraction is that theoretical models are more easily imagined. The user must have an intuitive grasp of its possibilities, a good model being one that suggests much speculation about the original phenomenon.

The *'archetype'* model, the most abstract of all the classificational types, is seen by Black (1962) as 'a systematic repertoire of ideas by means of which

a given thinker describes, by analogical extensions, some domain to which these ideas do not immediately and literally apply. Thus, a detailed account of a particular archetype would require a list of key words and expressions, with statements of their interconnections and their paradigmatic meanings in the field from which they were originally drawn.' Thus Lewin's (1947) 'field model' in the social sciences uses terms such as 'vector', 'force', 'boundary', 'fluidity' in describing social phenomena.

How are models used in the sciences?

In a scientific context, the word model has varied meanings but tends to be restricted in its uses to 'invented ideas' which attempt to explain why aspects of the natural and man-made world behave as they do. Although there has been heated debate about 'The scientific method' (Cawthorn and Rowell 1978), the Popperian view of the place of models in science can be seen to be recently gaining wider acceptance in the way 'scientific method' is being overtly presented in science textbooks. An example of this is seen in Wenham *et al.* (1973).

Since our knowledge of the behaviour of the physical world can never be complete, it follows that our knowledge of the causes of that behaviour can never be certain. The best we can do is to guess (intelligently) some likely cause and to build imaginative pictures of the processes which give rise to the observed behaviour. These imaginative theories or models, as these pictures are called, have been the essential features of scientific speculation throughout its recorded history. There are imaginative adventures of the mind and they bring the essential ingredient of creativity into science.

Kac (1969) has suggested that models in science 'are for the most part caricatures of reality, but if they are good, then, like good caricatures, they portray, through perhaps in a distorted manner, some of the features of the real world. The main role of models is not so much to explain and predict—although ultimately these are the main functions of science—as to polarize thinking and pose sharp questions. Above all, they are fun to invent and to play with, and they have a peculiar life of their own. The "survival of the fittest" applies to models even more than it does to living creatures.'

Models have a variety of functions in relation to the advancement of science. These functions include:

(1) Models enable a simplified version of a phenomenon to be produced and therefore concentrate attention on special features of that phenomenon.
(2) They stimulate investigations, supporting visualization of a phenomenon and imaginative projection.

Kac has also suggested that scientific models are developed for two main reasons—to account for observed phenomena or to elucidate delicate and difficult points of a theory. In either case, models take up an intermediate position between observed reality and theory.

This intermediate position of models between observed reality and theory is also apparent in both the 'inductive' and 'hypothetico-deductive'

views of scientific reasoning. On the inductive scheme (Forcese and Richer 1973, Harré 1972), models provide a vital ingredient in uniting facts towards the formulation of theory. In terms of the more popular hypothetico-deductive scheme Popper's (1962) theory is applied through the model.

It is not always easy in science to draw a sharp dividing line between any two of the various types of models detailed by Black (1962). Also, a particular type of model for a certain phenomenon may well develop from another type of model. For example a scale or analogue model may be refined into a mathematical model; the qualitative billiard-ball model of a gas can be described symbolically and discussed deductively in mathematical terms. Alternatively, sometimes a mathematical description is made first and an analogue model developed later. Harré gives a good example of this: the mathematical equations describing the adjustments of hearing between two ears were obtained first and later an analogue model was evolved based on a switching mechanism. In the physical sciences, in particular, theoretical models evolve into mathematical models, although in this process the theoretical model must be greatly simplified.

How are models used in science teaching?

With respect to scientific knowledge, a scientist develops a 'mental' model of an aspect of reality, for example of an atom. This hazy, possibly self-contraditory, mental picture has been developed by the scientist in a variety of ways:

(1) From direct experience of reality through continued experimental situations and through the imaginative use of analogy, previous experience, and knowledge of theory.

(2) Through attempting to develop clear analogue, theoretical (verbal and diagrammatic) and mathematical models so that the ideas can be communicated to others. (As all teachers know, a mental model is clarified considerably in the attempt to communicate aspects of it to others!)

(3) Through learning from the iconic, verbal, diagrammatic and symbolic representations of the analogue, theoretical and mathematical models of other scientists.

The problem in science education is to develop a student's mental model of a phenomenon towards scientists' mental model. In the widest sense, this is a communication problem in that it requires the establishment in the student of a mental picture. This is achieved by means of iconic, verbal, diagrammatic and symbolic (mathematical) representations, and by confronting the student with contrived situations (experiments) which focus on aspects of reality.

With respect to the content of science which is to be taught at any particular educational level, naturally the range of model classes and the examples from a given class, should be limited by the age of the learner, in accordance with Piaget's theory of intellectual development. In view of the

evidence from the USA (Arons 1976) that even at university level approximately 50% of all students are still operating at the concrete operational level of thinking, the use of scale and simple analogue models seems widely justified whilst more abstract mathematical models have to be used with caution. However against this limitation on the range of types of models and on the examples from a class dictated by learning theory, the downward pressure of sophisticated examples and classes from research through undergraduate teaching to school-level teaching is continuous and perhaps inevitable. Few models used by teachers seem to have been developed primarily as heuristic devices for school-level work.

With respect to students' scientific skills, science teaching should be concerned, in part, with developing reasoning abilities required for model building and model evaluation. But, as Holman (1975) noted, there is a general absence of teaching about the 'theory and use of models' in science education and this is complemented by a lack of opportunity in most science classrooms to develop tentative models and to critically evaluate predictions from these models.

The use of models in teaching: difficulties and problems for educational research

The argument that models should be used more extensively in teaching has its opponents. For example, Gebert (1969) argues that 'most students regard models either as physical realities or as a mere hypothesis adding little to understanding of the subject. They have great difficulty in using models freely as required by the situation. This could well be the result of teaching models before they can be understood.' As Levine (1974) has pointed out, in any topic area there exists a hierarchy of models of increasing power of representation and prediction. What are the consequences of not teaching the scope of models and the principles of model building? Students tend to use the model most readily to hand, disregarding some of the factual material under consideration. This section will point to some of the problems associated with the use of models and to the research questions these suggest. It will also review the research that exists and propose a general strategy for teaching and investigation.

What are the general difficulties that students meet in relation to models? Four such general difficulties may be drawn attention to.

(1) A lack of awareness on the students' part of the intellectual boundary between the model, its source, and the explicandum. This is manifest as a general lack of awareness of the properties of the model, its source, and the explicandum, for example in the case of using 'waves' to describe sound whilst being insufficiently aware of the properties of waves in water. This can be overcome by teaching the model, either inductively or deductively, simultaneously with practical work on sound waves and water waves.

(2) Although students may have been introduced to a range of models of the same class in a given topic area, they persist in the use of the

most rudimentary. As Grotz (1977) says: 'Conceptual maturity can be prevented by preoccupation with an insufficiently refined model.' Perhaps the hesitancy to use the more advanced, and therefore more abstract, models is an indication of insufficient intellectual development, in the Piagetian sense. This will be discussed later.

(3) Students find it difficult to apply a given model in different contexts. Greater opportunity, perhaps encouraged by a reduction of algorithm-application questions in examination papers, would help here.

(4) Students find problems in relating models of different classes within the same topic area, for example the Unit Cell (analogue) and stoichiometry (mathematical) in crystallography, or the Kekulé model (analogue) and Ingoldian mechanisms (theoretical) in organic reactions. Again, lessons devoted to models should help.

The processes of evolving schemes for the teaching of appropriate models and modelling are complex. There are, however, some pointers already available in the literature. The disadvantages of using an 'historical' approach, i.e. introducing models in the order of their discovery or evolution, have been pointed out by Levine (1974); the main difficulty is that the logical processes associated with each are somewhat different, not readily accessible, and not necessarily relevant to students' needs. The relationship between particular models and the associated theories have not often been spelt out in forms appropriate for teaching purposes: Cavagnol and Barnett (1976) have discussed this problem in general terms, whilst Klainin (1976) and an Open University course team (1972) have tackled the case of 'models of the atom and bonding'. Although the particular problems with mathematical and analogue models, to be discussed next, will offer an opportunity to present ideas for those respective areas, an increased integration between theoretical and practical, between qualitative and quantitative approaches, seems called for.

In the field of mathematical models, the evolution of practical approaches to teaching is likely to be promoted by the new *Journal of Mathematical Modelling for Teachers* (1978). The advent of programmable calculators offers broad opportunities for individual work by students in developing and evaluating mathematical models: the field has been reviewed by Beare and New (1977) and by Summers (1978), whilst Eisberg (1976) has developed an extensive theoretical and practical guide. Computers are already extensively used in the field of mathematical modelling, the N.D.P.C.A.L.‡ (Hooper 1977) having made a major contribution in the UK, and Dorn (1975) has pointed out the wide range of roles which computers can have in learning. With respect to models in science teaching, computer-assisted learning (CAL) enables

(*a*) More sophisticated, although often conceptually simpler, models to be introduced to students.

‡ N.D.P.C.A.L. denotes the National Development Project for Computer-Assisted Learning.

(*b*) The students to explore, control and manipulate properties of the model.
(*c*) Simulated 'experiments' to be carried out early and quickly so that students can easily investigate their own hypothetical models.

Undoubtedly CAL has considerable attractions for teaching students about particular models and has considerable relevance in encouraging students to develop and evaluate their own tentative models. Further work in investigating the potential and limitations of CAL with respect to models in science education would appear very desirable.

In the area of analogue models, two major misunderstandings may be identified:

(i) Students tend to mix their analogies, for example they make 'the assertion that heat [taught as if it had fluid qualities] makes molecules vibrate. Heat here is both thought of as something separate from and independent of the molecules and as also being a state of the molecules' (Schools Council 1970). Perhaps heat (a process) is being confused with molecular vibration (an effect) (Warren 1978).
(ii) Wicken (1976) feels that many models are presented as being actual reality, i.e. as being 'true', so that students are led into acquiring technical skills to solve problems in terms of the 'true-model'. Consequently, a sense of subject development is lost. Certainly this would explain students' reluctance to abandon a particular model, and their apparent sense of betrayal when the shortcomings of the model are finally revealed.

In addition to these difficulties with analogue models, several issues arise from the theoretical treatment given earlier in this paper. These may be summarized by the following questions.

(1) Do misunderstandings arise because students fail to ascribe correctly Hesse's positive, negative and neutral status to parts of the analogy?
(2) Do students fail to see the distinction between proportion and analogy?
(3) Are the 'conventions of interpretation' relating a model to reality fully appreciated by all students? Thus, do students find difficulty in defining the extent of a similarity between properties of a model, its source and the explicandum? After all, these similarities can vary from a virtual identity to an extremely weak, and hence difficult to perceive, relation.

Again, a suitable framework for both educational research and teaching might be to develop formal instructional sequences in relation to specific systems of models. The practical approach of Snadden (1977) might be linked to the theoretical approach to analogy-building as advocated by Schon (1963). Problems in the area of 'visualization' would also seem to be of value.

Johnstone, Letton and Percival (1977), feeling that one of the main problems in regard to three-dimensional structures was their relation to two-dimensional representations, devised a tape-slide programme associated with diagrams and manipulable models, with apparently encouraging results. The apparent importance of visualization skills in understanding chemistry was supported by Baker and Talley (1972) who correlated performance on visualization tests with performance in chemistry examinations, to show a quite good relationship. In later work, Baker and Talley (1974) showed that performance on visualization tests correlated well with performance on paper-and-pencil analogy questions ('the language counterpart of visualizing activity'). Other work on visualization has been undertaken by Dickson (1974) and Cleary (1975), whilst Carrier and Clark (1977) have called for greater attention to this subject.

The parallels drawn earlier in this paper, between the processes of science and methods of science teaching, can also be explored in practical classes.

(*a*) Although Black's analysis is concerned with the types of models used in research, there seems little doubt that the same models are being used for the very different process of teaching. To take a notional and extreme case, it is conceivable that a particular model, originally produced as part of an inductive exploration of a field, is now used for the deductive exposition of that field. How is this difference manifest?

(*b*) To what extent, and in what particular instances, is science taught in an inductive manner? What kinds of misunderstanding are generated if, during teaching in an inductive manner, students fail to generate generalizations between a collection of apparently related observations or facts?

(*c*) To what extent, and in what particular instances, is science taught in a deductive manner? What kinds of misunderstandings are generated if, during teaching, in a deductive manner, students fail to appreciate 'the rules of inference' and the 'correspondence rules'?

Finally it is suggested that to investigate the various hypotheses that have been put forward, and the different sources of misunderstanding that have been identified, the following kinds of activity should be fruitful.

(i) Examining students' actual use of models, for example in solving problems, or in practical classes, and in understanding.

(ii) Providing special classes on the theory and use of models, in which difficulties could be revealed and remedied.

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